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14. ABSTRACT

This work investigates the multiscaled structure and the constitutive behavior of the exoskeleton of arthropods (Japanese beetle) along with the response of biomimicked structures. Image analysis (SEM and TEM) revealed three load-bearing regions comprised of chitin-protein fiber layers orientated parallel to the cuticle surface. The chitin fibers in the exocuticle and mesocuticle are organized in a helicoidal structure (layers stacked with a small rotational angle relative to their adjacent layers). The endocuticle has a distinct pseudo-orthogonal pattern, characterized by a thin transitional helicoidal region inserted between two orthogonal layers. Idealized mechanics based models showed that the pseudo-orthogonal structure redistributes the stresses, and reduces the maximum tensile stress and transverse shear stress in the cross-section, thus making the structure able to tolerate larger external loads. Furthermore, the interfacial strain energy release rate is lower in the pseudo-orthogonal structure compared to the cross-ply laminate, suggesting that the pseudo-orthogonal structure may be more resistant to fracture. The bio-inspired laminated composite structures, designed and manufactured, showed improved mechanical properties over the conventional industry standard structure

15. SUBJECT TERMS

biomimicking, composite materials, durability

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Final Report ARO W911NF-08-1-0493

High Strength and Light-weight Materials Inspired by the Exoskeleton of Arthropods

Anette Karlsson, Dept. Mechanical Engineering. University of Delaware, January 2010

Objectives

The overall objective of the proposed work was to establish the multiscaled structure and the constitutive behavior of exoskeleton of arthropods. The following tasks are defined for the proposed short term investigation: (1) Establish the morphology of the multiscale structure for selected exoskeleton materials through careful and systematic image analyses; (2) Explore the mechanical properties; (3) Simulate characteristic structural response of the exoskeleton using mechanics based numerical models and investigate how these structural responses can be translated into engineering materials.

Summary of Results

(1) Morphology of the multiscale structure for a Japanese Beetle

We investigated the exoskeletal microstructure of a common insect, *Popillia japonica* (Japanese beetle). This structure was compared to a previous study, where *Homarus americanus (American lobster)* and *Callinectes sapidus* (Atlantic blue crab) were investigated [1].

Image analysis via SEM and TEM revealed a common morphology in cuticles from the pronotum, leg and elytron. All exoskeletons consist of four regions, including (from external surface and inwards and corresponding to increasing thickness) epicuticle, exocuticle, mesocuticle and endocuticle, fig. 1 [2]. The latter three regions are the load-bearing structures and are comprised of chitin-protein fiber layers orientated parallel to the cuticle surface. The chitin fibers in the exocuticle and mesocuticle are organized in a helicoidal structure, which is characterized by layers stacked with a small rotational angle relative to their adjacent layers, Fig 1B, Fig. 2A, B. The endocuticle has a distinct pseudo-orthogonal pattern, which is characterized by a thin transitional helicoidal region inserted between two orthogonally stacked layers Fig. 2C, Fig 3.

Idealized mechanics based models of orthogonally layered structures with and without the helicoidal transitional region (corresponding to the pseudo-orthogonal and conventional cross-ply laminates respectively) were developed for evaluating the endocuticle's mechanical response within the linear elastic range, Fig. 4. The mechanical response of the conventional cross-ply laminate includes discontinuity of the normal stress (Fig 5A) and transverse shear strain (Fig 6B) at the interfaces of the orthogonal laminae due to the discontinuous material properties (assuming laminate theory within the framework of continuum mechanics). The introduction of a pseudo-orthogonal structure results in a redistribution of the stress and strain fields, including smaller discontinuities between the layers and more uniform stress and strain distribution over the cross-section, Figs. 5 and 6. The pseudo-orthogonal structure results in reduced maximum tensile stress and transverse shear stress in the across-section. The magnitude of the discontinuity (jump) in the normal stress and shear strain is significantly reduced as well. Furthermore, the interfacial strain energy release rate of the laminate is lower in the pseudo-orthogonal structure compared to the cross-ply laminate, suggesting that the pseudo-orthogonal structure may be more resistant to fracture.

Laminated composite structures were designed and manufactured with bio-inspired structural patterns. To investigate how the layup sequence affect man-made materials, four model configurations characterized by distinctive stacking-sequence were developed: (1) a baseline structure (BL), which is widely used in industry as a quasi-isotropic structure; (2) a "single helicoidal" structure (SH) with its stacking sequence directly replicated from the nature designed helicoidal structure; and two variations (3) a "double helicoidal" structure (DH) and (4) a "single helicoidal mid-plane symmetric" structure (SHMS). The last two configurations were developed to address the mid-plane symmetry issue. Uni-directional S2-glass epoxy prepreg was used as model material. We note that we do *not* believe this is the best suited material system, but believe this well-known material system may reveal imported structural implications. The mechanical performance was evaluated via standard test protocols (ASTM D790 and ASTM D2344), including the flexural stiffness and strength, transverse shear modulus and strength, as well as residual strength. The bio-inspired structure showed improved mechanical properties over the conventional baseline structure that is widely used in industry, including the bending stiffness (Fig. 7) and the residual strength under static load (Fig. 8). The improvement was more significant when a "smaller" fiber rotation was used, such as the SH and SHMS structures. Also, the warping problem during practical manufacturing was addressed by enforcing mid-plane symmetry in the laminate design; meanwhile the mechanical advantages of the bio-material system were still retained. The improvement on the mechanical performance observed in the bio-inspired structure underscored the advantages of the helicodial structural pattern. With proper combination with the practical manufacturing wisdom, such as mid-plane symmetry, the nature designed helicoidal structure possessed great potential in future practical application.

Conclusion

The results reveal interesting aspects of the strategy of the nature in designing and manufacturing functional biomaterial systems. These observations may be used to inspire and improve man-made materials and structures. Preliminary work indicates that the layup have clear potential for superior residual strength after initial failure.

References:

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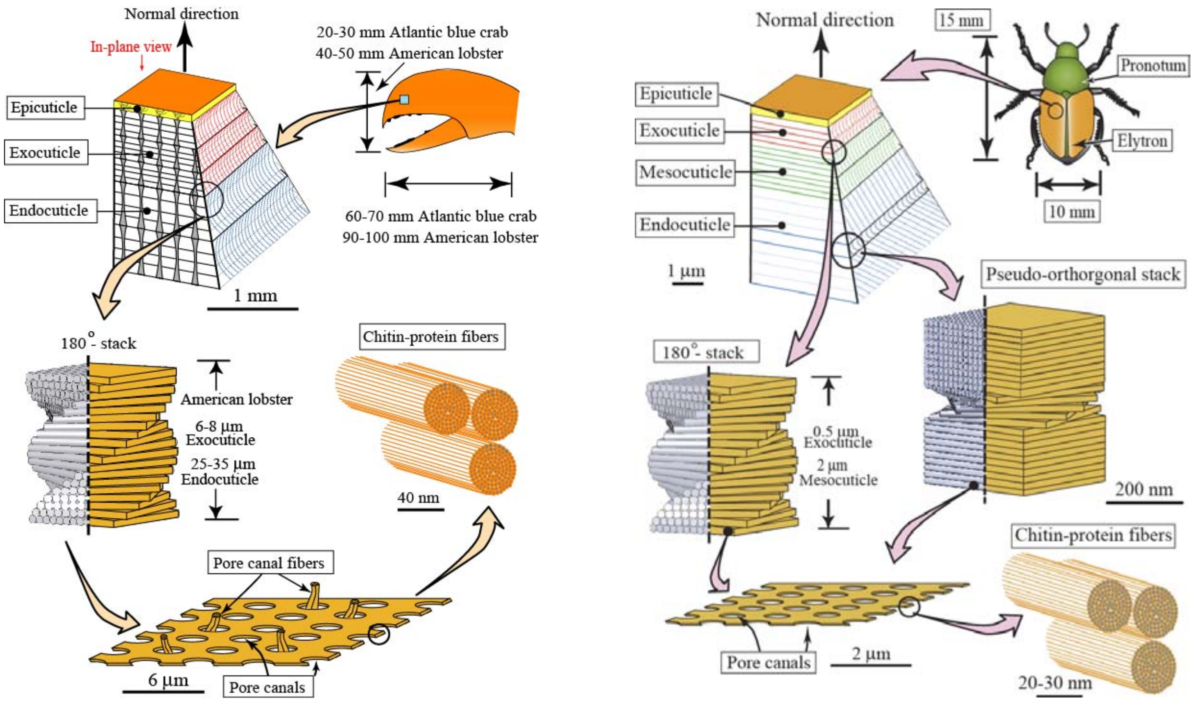
[2] Cheng L, Wang LY and Karlsson AM,, Mechanics based analysis of selected features of the exoskeletal microstructure of Popillia japonica, J Materials Research, 24(11) 3253-3267 (2009)

[3] Cheng L, Glancey JL and Karlsson AM, Mechanical behavior of bio-inspired laminate composites, *in review*



(A) Blue Crab and Lobster **(B) Japanese Beetle**

Fig. 1 *Schematic of the upper structural levels of a (A)* Homarus americanus *(American lobster) exoskeleton [1] and (B)* Popillia japonica *(Japanese beetle) exoskeleton [2]. In both cases, the epicuticle, a diffusion barrier, is not a structural load bearing layer The exocuticle, mesocuticle (beetle only) and endocuticle are the main load bearing structures composed of fibrous chitin-protein fibers organized as either helicoidal or pseudo-orthogonal structures.*

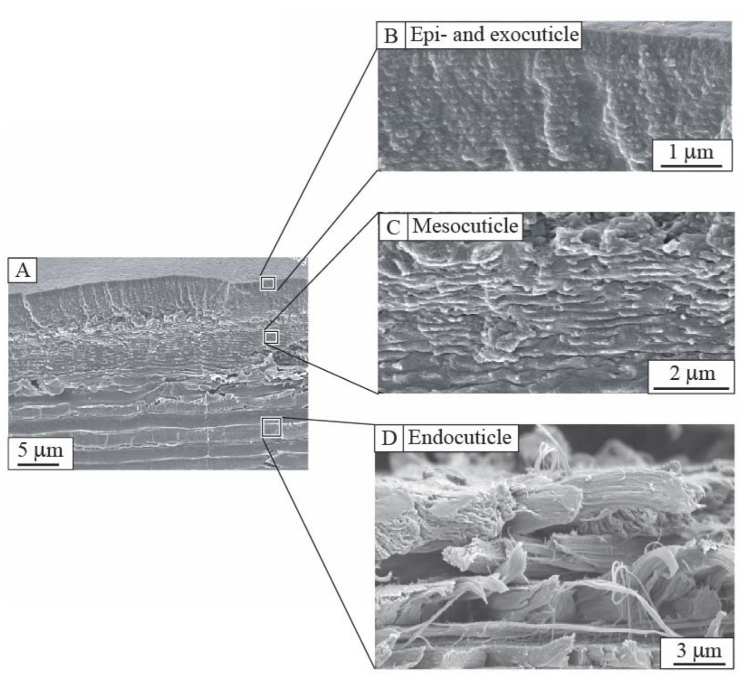


Fig. 2 *SEM images of the exoskeleton (elytron) of a* Popillia japonica. *(A) Overview of the cross-section; (B) Epicuticle and exocuticle (~2 µm thick); (C) Mesocuticle (7-7.5 µm thick); and (D) Endocuticle (10-11 µm thick). The stacking of two orthogonal layers is shown in the endocuticle.[2]*

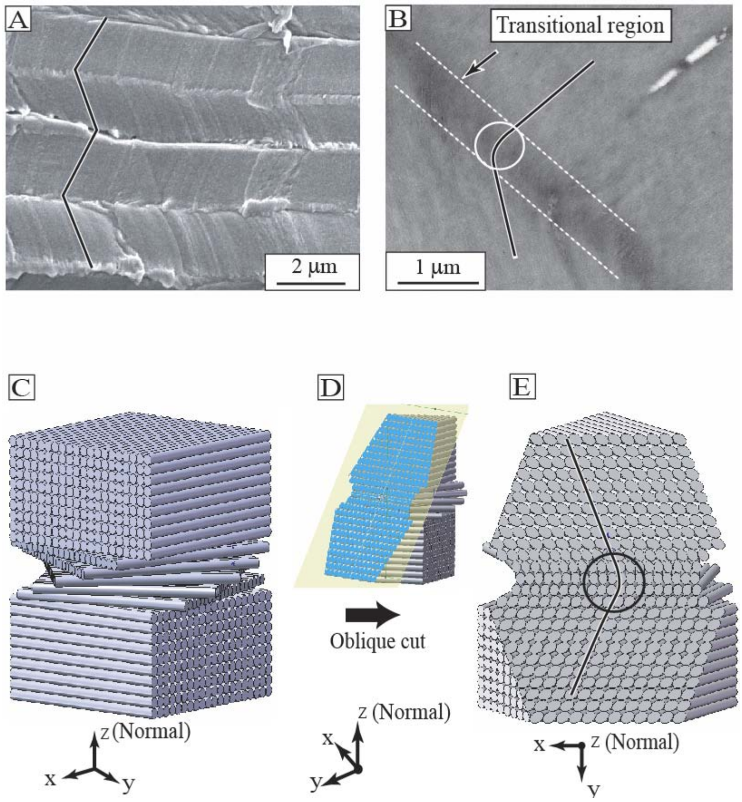


Fig. 3 *The pseudo-orthogonal pattern of the chitin-protein fibers in the endocuticle. (A) A zigzag pattern seen in a SEM image of an oblique section of the endocuticle from the* Popillia japonica *elytron; (B) A TEM image of an oblique section of the endocuticle, suggesting a helicoidal transitional region (parabolic pattern) between the two orthogonal layers (the size of the transitional region appears to be thicker than the true thickness since it is observed from an oblique section); (C) A schematic representation of the pseudo-orthogonal pattern: The two orthogonally stacked unidirectional layers each consists of parallel fibers. A thin transition region assembling a helicoidal structure (Bouligand-structure) joins the two orthogonal layers; (D) An oblique cut in the pseudo-orthogonal block; (E) The side view of the oblique cut displays the zigzag and parabolic pattern seen in (A) and (B). [2]*

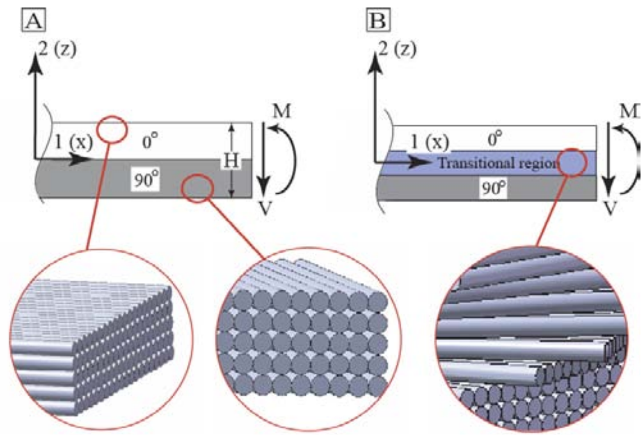


Fig. 4 *Models of (A) the traditional cross-ply laminate and (B) bio-inspired pseudo-orthogonal laminate of thickness,* H. *The cross-sections of the laminates are subjected to the general load of bending moment* M *and shear force* V *(load* per unit width*). The schematic enlargement of each region indicates the fiber orientation in the corresponding region. [2]*

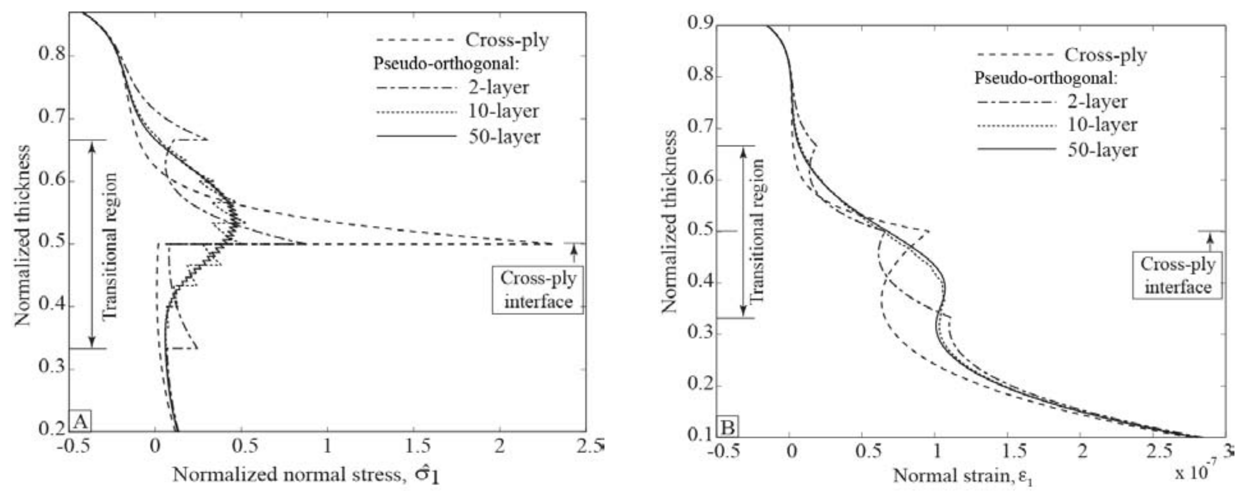


Fig. 5 *(A) Normalized normal stress and (B) normal strain distribution over the cross section of the laminate with selected numbers of lamina in the transitional region.[2]*

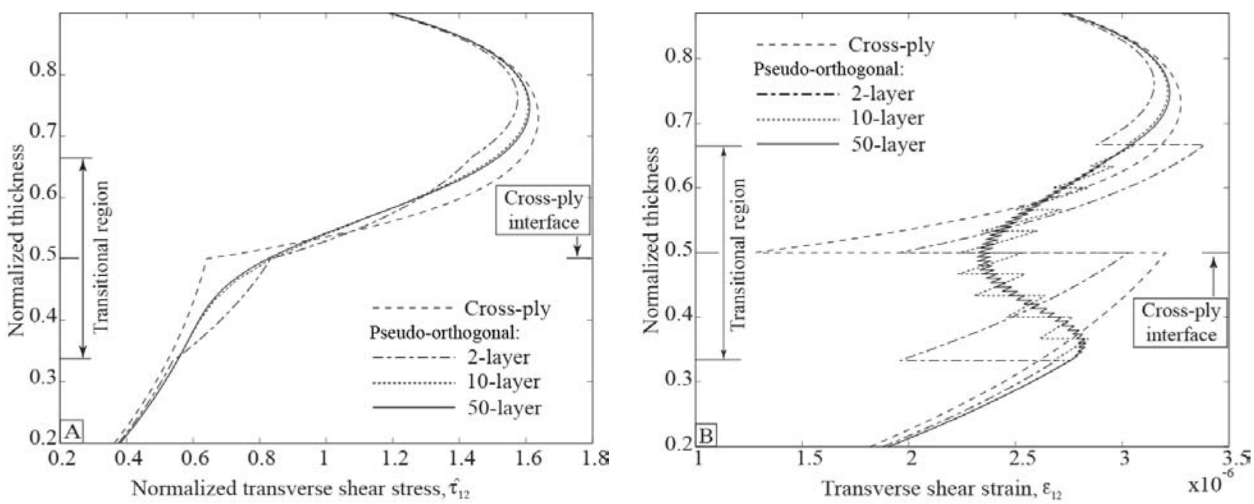


Fig. 6 *(A) Normalized transverse shear stress and (B) strain distributions over the cross section of the laminate with selected numbers of lamina in the transitional region. [2]*

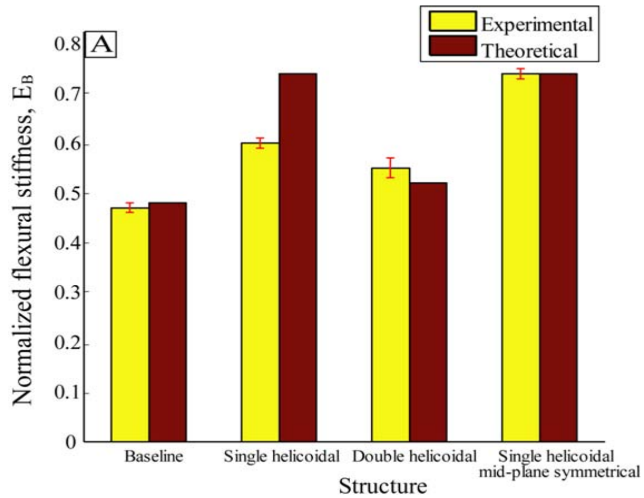
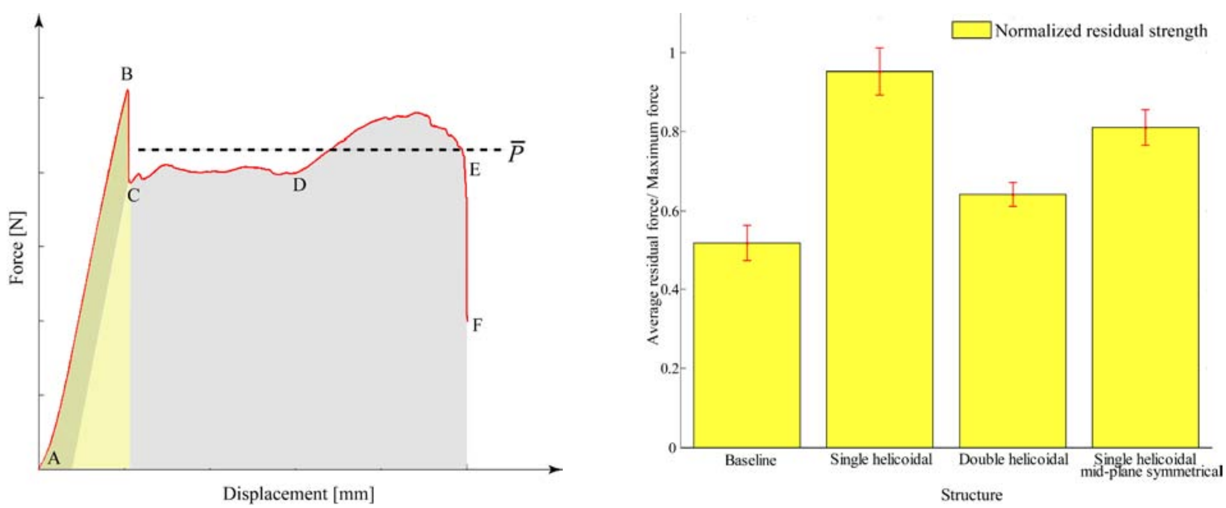


Fig. 7 *Normalized flexural stiffness of laminates beams with different structures from the "long beam test" (ASTM D790). [3]*



(A) (B)

Fig. 8 (A) *A typical force-displacement curve from the "short beam test" (ASTM D2344).* $\overline{\boldsymbol{P}}$ *is the average residual force after the onset of initial damage. (B) Normalized residual strength of laminated composites with different structures. The red bar indicates the standard deviation of the result in each group. [3]*